

## Viewpoint

### The Weak Stability Boundary, a Gateway for Human Exploration of Space

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#### Abstract

NASA plans for future human exploration of the Solar System describe only missions to Mars. Before such missions can be initiated, much study remains to be done in technology development, mission operations and human performance. While, for example, technology validation and operational experience could be gained in the context of lunar exploration missions, a NASA lunar program is seen as a competitor to a Mars mission rather than a step towards it. The recently characterized Weak Stability Boundary in the Earth-Moon gravitational field may provide an operational approach to all types of planetary exploration, and infrastructure developed for a gateway to the Solar System may be a programmatic solution for exploration that avoids the fractious bickering between Mars and Moon advocates. This viewpoint proposes utilizing the concept of Greater Earth to educate policy makers, opinion makers and the public about these subtle attributes of our space neighborhood.

#### Introduction

NASA has been pursuing the idea of human exploration of the Solar System since the mid-1980s, when, in the wake of the Ride report[1], it established an Office of Exploration at NASA Headquarters. The studies conducted in the office concentrated on two human exploration options presented in the report, Outpost on the Moon and Piloted Missions to Mars. An external constituency developed for each of these options. The advocates assumed that only one of the choices would become the next human program in NASA. Consequently, a certain degree of hostility developed between the two communities, which continues to this day.

Currently, NASA has an active program for robotic exploration of Mars and has published a potential scenario for human exploration of the red planet. No similar program or scenario exists for the Moon. Indeed, concerns have been expressed that a lunar program of human activity would create a constituency among certain companies and institutions that would benefit from indefinite continuation of the program and thereby thwart any new initiatives towards Mars. Such concerns may well be legitimate. Nevertheless, I believe there is a 'third way' through the Moon or Mars dilemma and will propose here a strategy within the NASA context for initiating human exploration of the Moon and Mars.

#### Barriers to Human Exploration of Mars

The obstacles confronting human planetary exploration remain many and serious. A round-trip mission to Mars lasts roughly three years and requires launchers larger than we have available today. The systems for interplanetary transportation and for planetary surface operations must reliably preserve crew safety, crew health and crew performance. Using nuclear propulsion could shorten the mission duration, but that option appears to be both too expensive to develop and politically unacceptable. The long mission raises questions about human health and performance that are not answerable within our current knowledge base. We have no data on

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the reliability of complex space systems over the time span required. The communication delay at the distance of Mars creates an operational regime in which our current experience in human missions is inadequate.

All these questions can be addressed by spending money wisely over a number of years. If NASA were to propose a human Mars program to the Administration and the Congress, the development schedule would be extensive and the cost would be high. Given the track record with the International Space Station, any estimates of time to completion and of total cost would be viewed sceptically. In effect, no Mars exploration program can be proposed until uncertainties are reduced significantly; but no work can be done on the problems until a program is authorized. We have gridlock.

The solution is straightforward, in principle. Create programs that address one or more of the issues associated with human missions and that have worthwhile (i.e., politically saleable) objectives and products of their own. In practice, implementation of the principle is a challenge. A modest, low-key program involving astronauts in space is an oxymoron.

In 1991, I wrote a paper suggesting that technical and operational solutions to the challenges of human exploration of Mars could be tested and validated in a program of lunar activities.[2] For example, lunar landings could have durations of days (within Apollo experience base) to years (needed for Mars experience base). The mean time between failures for key life support system elements in a planetary surface environment could be determined. Durability and mobility characteristics of spacesuit designs could be tested. The long-term physiological effects of a low-g environment could be measured.

Unfortunately, this proposal runs up against NASA Administrator Dan Goldin's concerns that we would never get to Mars. The NASA culture regards its current program (whatever it may be) as the top priority; engineers might spend their time solving lunar-specific problems, forgetting the imprimatur to prepare for Mars. Finally, a lunar program would be viewed as victory for one side and defeat for the other in the 'Moon vs. Mars' religious wars. It would be bitterly contested in the political processes.

In 1998 Wes Huntress, then Associate Administrator for Space Science at NASA Headquarters, suggested that it might be necessary to utilize astronauts to deploy the Next Generation Space Telescope in deep space.[3] The location would be a Lagrange point of the Earth-Sun system, located more than a million kilometers beyond the Earth from the Sun. One of the benefits of this proposal would be the development of spaceships eventually capable of taking humans to Mars. The development cost would be associated with the telescope project and not part of a Mars exploration project. The suggestion was tabled after some technical analysis, but the point was to use an intermediate objective to develop the tools for Solar System exploration. And it is another intermediate objective that I believe could be used to enable both lunar and martian missions. To explain my idea, I must first discuss a little-known property of the gravitational field of the Earth-Moon system.

### The Weak Stability Boundary

Everyone is familiar with the concept of one body orbiting another. What most do not realize is that both bodies actually revolve about the center of mass of the combined system, a point called the *barycenter*. When one body is very much more massive than the other, the barycenter is located very close to the center of mass of the larger body. Thus, there is nothing wrong with saying a satellite orbits the Earth.

When the two bodies are of comparable mass, the barycenter can lie at a point external to and between both bodies. In the case of the Earth-Moon system, the barycenter is located inside the Earth, about 75% of the way to the surface from the center.

Imagine a very long, thin, stiff wire strung through the centers of mass of the Earth and the Moon. We could slide a tiny bead along that wire to a point where the gravitational pull of the Earth just balances the gravitational pull of the Moon. The balance point would be much closer



to the Moon than to the Earth. The location of the bead is unstable because a slight push would cause the bead to slide toward one of the planets.

Now suppose our planets are revolving about their barycenter, which also lies on the wire. In this case, the bead would be affected by the centrifugal force of the rotation in addition to competing gravity from the two planets. To balance all three effects, the point of equilibrium would be at a somewhat different location than before. In the rotating system, the unstable point of balance is called the interior Lagrange point; and I will refer to it as  $L_1$  in this paper. It is located about 5/6 of the way to the Moon from the Earth.

There exists another unstable Lagrange point on the far side of the Moon where the centrifugal force of rotation is balanced by the cooperating gravitational pulls of the two planets. In my notation, the point on the far side of the Moon is called  $L_2$ . An analogous point  $L_3$  exists on the far side of the Earth. For completeness, I note that two more "stable" Lagrange points exist along the orbit of the Moon, about  $60^\circ$  off the line from the Earth to the Moon. (The stable points are where some groups have proposed to locate space colonies.)

The three unstable Lagrange points lie within a connected space called the *Weak Stability Boundary* (WSB) by Ed Belbruno.[4] An object not sitting at a Lagrange point can remain within the WSB if its velocity happens to counter the planetary gravity and the effects of the rotating coordinate system. Objects moving within the WSB do not have the kinetic energy necessary to fully escape the Earth-Moon system, but neither are they captured by the Earth itself nor by the Moon itself. It becomes possible to move large distances within this somewhat mysterious limbo using low thrust propulsion. Too much thrust can impart enough kinetic energy to exit the zone into deep space or into the grasp of one of the planets.

Bob Farquhar established many years ago that closed trajectories could be maintained in the vicinity of the unstable Lagrange points by utilizing a small amount of thrust for station-keeping. He characterized these trajectories as *halo orbits*, even though they were complex 3-dimensional lissajous figures rather than conic sections. He demonstrated a halo orbit for a communications relay satellite in the vicinity of the lunar  $L_2$  point, approximately 60,000 km beyond the Moon.[6] From the point of view of an antenna on the Earth, the satellite would appear to oscillate slowly above the limb of the lunar disk. The satellite could relay signals from the Earth to points on the surface of the far side of the Moon.

Belbruno has shown that a new type of low energy transfer from the Earth to the Moon can be constructed using the WSB.[4] The concept was demonstrated operationally with the Japanese Hiten spacecraft in 1991. In 1999 a communications satellite was left stranded in a highly elliptical geosynchronous transfer orbit by a failed fourth stage on the launch vehicle. Using techniques similar to Belbruno's the apogee of the satellite was raised gradually using the onboard nitrogen gas thrusters. As the satellite entered the WSB, it was maneuvered around the Moon twice and finally settled into an Earth orbit at geosynchronous distance at  $10^\circ$  inclination. At that location, services on the satellite could be marketed. Recently, Belbruno and Carrico have developed a technique for finding trajectories that allow spacecraft to be inserted into lunar orbit without the hitherto required insertion burn from an onboard engine.[5]

The WSB volume has several intriguing properties. It provides a low-energy (but low speed) corridor between the Earth and the Moon. In that sense it is like a canal on the Earth, which provides a low-cost, slow connection for commerce. The WSB also acts like a skin, separating deep space from Earth-Moon space. Once into the WSB, escape to interplanetary travel is energetically cheap. The WSB provides volume for storage of facilities in halo orbits, each of which can be reached from others with low energy investment. The thrust needed for station-keeping in a halo orbit is so small that it can be implemented with light pressure on a solar sail.[6] I believe that the WSB can be effectively utilized in a plan for human exploration of the solar system.



## A Gateway to the Solar System

Immediately after the formation of NASA, studies were done on the best mode of launching a human mission to the Moon. The favored mode was direct launch because a rendezvous in space was considered too risky.[7] However, the launcher required to directly place a spacecraft on the Moon was found to be too large to be practical. Given that a rendezvous was necessary, the favored location was LEO. As everyone knows, the lunar orbit option was finally used, although other choices were advocated, including a lunar surface rendezvous. In the latter case, a crew-return vehicle would be landed automatically at the lunar landing site before the crew departed from Earth in the landing vehicle. The health of the return vehicle could be verified by telemetry before the crew arrived. Interestingly, the surface rendezvous is currently the option of choice in human Mars mission scenarios.[8]

The lunar orbit rendezvous option places operational limitations on lunar missions. The orbit plane of the mother ship must pass through the landing site when the lander departs and again when the lander ascends to rendezvous. The Apollo landing sites were at low latitudes to facilitate orbital adjustments to enable the alignment at the crucial times. High latitude sites would require high inclination orbits, and alignments would occur infrequently. Making the rendezvous in LEO (e.g. with the ISS) also requires orbital alignments, making lunar operations dependent on launch windows.[2]

Mission design studies have considered  $L_1$  as a rendezvous location.[9] All lunar latitudes are accessible at all times. Conversely, the  $L_1$  point is accessible from all points on the lunar surface at all times. The location is also accessible from the Earth at all times.

Since the  $L_1$  point sits at the WSB, the additional energy required to escape completely the Earth-Moon system is quite low. Consequently, it makes an ideal departure point for interplanetary missions.[10] Some kinds of infrastructure for support of interplanetary missions could be stored in the vicinity of the  $L_1$  point using halo orbits. For example, NASA is currently considering low-thrust solar-electric vehicles for interplanetary transport of crew and of supplies to Mars. If such a vehicle were assembled in LEO, its journey out of the Earth's gravity well can take weeks using only its low-thrust engines. In particular, it will pass slowly through the Van Allen radiation belts. Mission scenarios call for the crew to be launched on a conventional chemical rocket to rendezvous with the interplanetary vehicle in high Earth orbit. Upon return to Earth, the crew would disembark at high Earth orbit. If the vehicle was designed for re-use, it could be stored at  $L_1$  in a halo orbit.

The idea of re-using interplanetary vehicles implies the capability to refuel, refurbish, and maintain them.[11] Crews could be launched from Earth to prepare the craft for its next mission. If the traffic were high enough to the Moon and to Mars and if other projects were being carried out, a permanent facility with life support could be built. I discussed such a station at  $L_1$  in a paper in 1993[12].

Uses for a space facility at the Lagrange point would be similar to plans for ISS, but the space environment is more amenable to many research activities when compared to LEO. At  $L_1$  there is no orbital debris, no atomic oxygen plasma, no need for reboost to maintain orbit, and no gravitational gradient to spoil microgravity experiments. Crews from the central station could maintain unmanned scientific facilities residing in the WSB, such as observational platforms or long-term experiments in weightlessness.

The Lagrange points lie outside the Earth's geomagnetic field. Crew and electronics would be vulnerable to solar particle events. The design and the operations planning would have to incorporate shielding and appropriate countermeasures should crew be exposed to radiation. Of course, these concerns also apply to the transit phases of missions to Mars and to activities on the Moon.

The WSB has one more important attribute: few people know about it and none of them have any emotional attachment to it. This statement may seem silly on the surface, but one of the barriers to implementation of human exploration is the 'religious' battle between Moon believers



and Mars believers. The development of tools, infrastructure, and capability to exploit the WSB can reduce the cost and risk of future exploration programs while avoiding negative reactions to a decision that could be interpreted as favoring a final destination for planetary development. Of course, the other side of the coin is that no one will connect with any proposals involving the WSB. What is the solution to this advocacy problem?

### The Concept of Greater Earth

Our conception of Planet Earth has increased in complexity during the twentieth century. We understand our environment in terms of layers of spherical shells. Moving from the center of the Earth outwards, we have the core, the mantle, and the crust. Enveloping the solid Earth is the life-giving atmosphere. The Russian ecologist Vernadsky coined the term *biosphere* to describe a metaphorical layer of life on the planet.[13] Recently, we have found the biosphere penetrates to considerable depths in the crust.

Pictures of the Earth from space spawned the environmental movement as people saw the finiteness of our world. Those pictures, however, fail to reveal invisible layers around the Earth that are also important to our survival. We now receive regular reports of space weather and have begun to understand the protection afforded to us by the magnetosphere. Pictures from orbit also fail to reveal another life-preserving component of our system – the Moon.

Planetary dynamicists studying Mars assert that the tilt of its rotation axis to the ecliptic (called its *obliquity*) changes over time in a chaotic manner, in the mathematical meaning of the term. Large excursions in obliquity have dramatic effects on climate and probably account for the current frozen, lifeless state of the planet. Analyses show that a similar fate would befall the Earth, except for the stabilizing influence of the angular momentum in the gravitational link to the Moon.[14] Our sister planet acts as a giant flywheel, keeping us more or less stable and maintaining the life support system so critical to life's evolution. Only when we can view ourselves from greater distances in the solar system will we truly understand the uniqueness of our double planet system.

Krafft Ehrlicke observed that God must have wanted us to be spacefaring species because he gave us a Moon.[15] Dr. Ehrlicke was referring to the convenient proximity of the Moon for developing our skills as planetary explorers. However, we now understand that the Moon creates another stepping stone to the solar system, the Weak Stability Boundary.

Before any kind of program can grow from these ideas, opinion makers, policy makers, space enthusiasts, and the public in general must attain some understanding of the potentialities for space utilization that exist in our neighborhood. I propose adopting the term 'Greater Earth', as presented by the European Space Agency committee on long-range policy, to express the concept of interrelationship and interdependence within the Earth-Moon system. The financial community realized that the Moon was not a remote, irrelevant object when the AsiaSat communications satellite circled the Moon twice and returned to Earth orbit using tiny gas jets. Similarly, those of us who want to explore must admit to our own ignorance of subtleties in the structure of the very space around us that could simplify the attainment of our goals.

I do not propose here a specific future project. Rather, I urge a dialogue to consider new approaches towards making human exploration beyond Earth orbit affordable and politically viable. We may think we are now ready to move out to the planets, but we still have much to learn and much to build within the context of Greater Earth.

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